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The wind power of Mexico

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ABSTRACT

The high price of fossil fuels and the environmental damage they cause have encouraged the development of renewable energy resources, especially wind power. This work discusses the potential of wind power in Mexico, using data collected every 10 min between 2000 and 2008 at 133 automatic weather stations around the country. The wind speed, the number of hours of wind useful for generating electricity and the potential electrical power that could be generated were estimated for each year via the modelling of a wind turbine employing a logistic curve. A linear correlation of 90.3% was seen between the mean annual wind speed and the mean annual number of hours of useful wind. Maps were constructed of the country showing mean annual wind speeds, useful hours of wind, and the electrical power that could be generated. The results show that Mexico has great wind power potential with practically the entire country enjoying more than 1700 h of useful wind per year and the potential to generate over 2000 kW of electrical power per year per wind turbine installed (except for the Chiapas's State). Indeed, with the exception of six states, over 5000 kW per year could be generated by each turbine.

Contents

1. Introduction

The processes of industrialisation and economic development require energy [1]. Combustible fuels are the world's main energy resource and are at the centre of energy demands [2]. However, the reserves of fossil fuels are limited, and their large scale use is associated with environmental deterioration [3]. This has encouraged growth in the use of renewable energy resources worldwide [4,5], including the use of biomass [6], tidal energy [1], solar energy [7] and wind energy [8].

Assessing the potential of the wind as a source of energy is an important goal of most countries with growing energy needs [9]. The major problem of wind energy is its unpredictability and the variability in the energy that can be harnessed at any particular time. This causes problems for the operators of electrical power systems [10]. In addition, the topography of the different areas where wind power might appear to be worth harnessing is very varied [11]; certainly, it would be hard to make use of all potential sites.

Numerous studies on wind energy have been concentrated on the mean wind speed [12,13] or the number hours of wind useful for producing electricity (i.e., with wind speeds of 3–21 m s^{-1} [14,15]). Certainly, wind farms need to be installed in areas that offer more than 1700 h of useful wind per year [16,17]. In Mexico, studies at state (rather than national) scale have examined mean wind speeds; for example, a statistical study on wind speed using data for the years 2007 and 2008 was performed for the State of Veracruz [18], and a study to predict the wind speed and direction in January 2008 was performed in the State of Oaxaca using data

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obtained over a 7-year period [19]. Mean wind speed maps have been produced for northern Mexico; in the region of the Isthmus of Tehuantepec, which has a mean daily wind speed of 7 m s^{-1}, it was estimated that wind turbines could generate up to 2000 kW each per year [20].

The aim of this work was to determine the wind power potential of Mexico, producing maps to show the areas of greatest potential in terms of mean annual wind speed, the mean annual number of useful hours of wind, and the electrical power that could be generated. The relationship between the mean annual wind speed and the mean annual number of useful hours of wind was also examined.

2. Materials and methods

2.1. Data

Data were collected from 133 automatic weather stations (AWS) around the country [21]; Fig. 1 shows their geographic distribution. The data used were those for 2000–2008, collected at 10 min intervals. A total of 6.41E+07 entries were examined.

2.2. Methods

The data were analysed using a computer program that determined the mean wind speed values for each 10 min period over each 24 h, thus providing the mean daily wind speed. The mean annual wind speed and mean multiannual (2000–2008) wind speeds were also calculated. The same program summed the number of hours per day during which the wind speed was over 3 m s^{-1} (i.e., the threshold speed of useful wind). From these figures the mean annual and mean multiannual (2000–2008) number of useful hours of wind were determined (Fig. 2).

The potential electrical power that could be generated was calculated by modelling the behaviour of a Gamesa G90-2.0 MW wind turbine [14], using the equation for the logistic curve below (Eq. (1)):

$$P_y = \frac{k \cdot y_0 \cdot e^{r \cdot x}}{k + y_0(e^{r \cdot x} - 1)} \qquad (1)$$

where P_y is the electric power generated, r the rate of increase, e is an exponent, and k is the capacity of the system.

The values of the variables in Eq. (1) were adjusted using MatLab© software. An R^2 value of 0.9987 and an adjusted R^2 value of 0.9985 was obtained for $k = 2016$, $Y_0 = 17.81$ and $r = 0.7664$.

3. Results and discussion

Table 1 shows the results obtained for the mean annual wind speeds for all of the 133 AWS together for the years 2000–2008. In all years the mean annual wind speed was above 2 m s^{-1}. The years 2001 and 2002 were much windier, with mean annual wind speeds of 2.85 and 2.76 m s^{-1} respectively. A map was produced showing the mean multiannual wind speeds for different parts of the country. Fig. 3 shows that the States of Nuevo León, Estado de México and Veracruz have mean multiannual wind speeds of 3–3.5 m s^{-1}. In fact, in Veracruz, mean multiannual wind speeds of >6.03 m s^{-1} were recorded at an altitude of 40 m above sea level, which agrees with results recorded by other authors [18]. The States of Baja California Norte, Baja California Sur, Oaxaca, the eastern part of the State of Chihuahua, the centre of the country, and the north of the Yucatán Peninsula, all had mean multiannual wind speeds of 3–5 m s^{-1}. The last of these areas is the best for generating wind power if this variable alone is taken into consideration. The rest of the country had mean multiannual wind speeds of <3 m s^{-1}; these areas would not be not suitable for the installment of wind farms.

Table 2 shows the mean annual number of useful hours of wind recorded by each of the 133 AWS. The years 2001 and 2002 again returned the highest figures with 3356 and 3024 useful hours respectively. The logistic curve for the modelled wind turbine allowed the electrical power that could be generated for each recording of a wind speed of >3 m s^{-1} to be determined. This allowed the annual potential electrical power that could be generated to be determined (Table 3). The years 2001 and 2002 were those of the greatest electricity generating potential at 14,030 and 16,116 kW per year for each 2 MW wind turbine installed. By way of comparison, Fig. 2 shows the mean annual wind speed

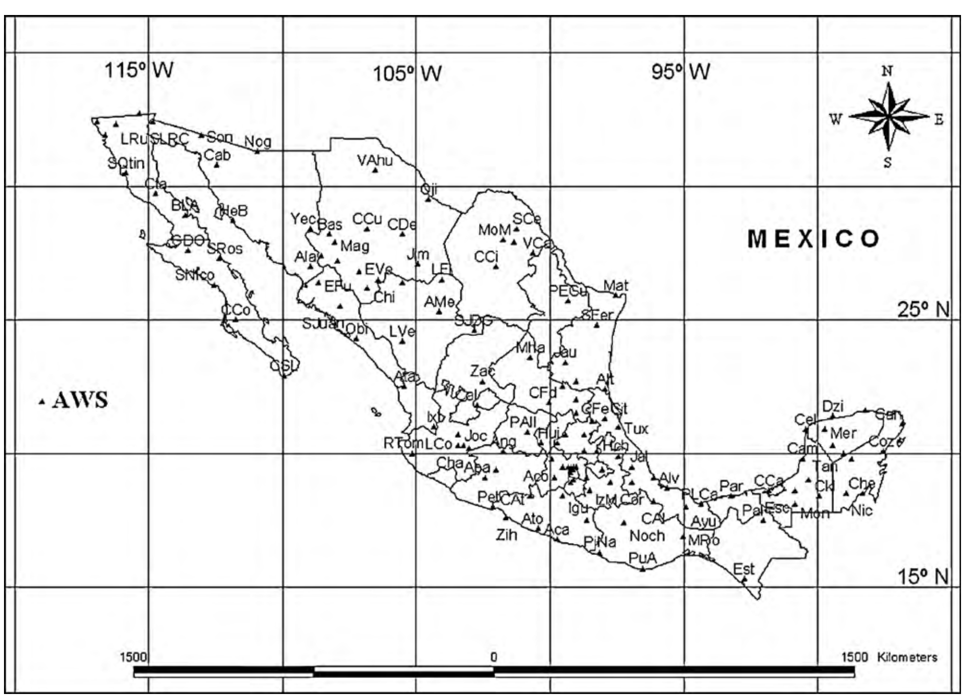

Fig. 1. Geographic distribution of AWS.

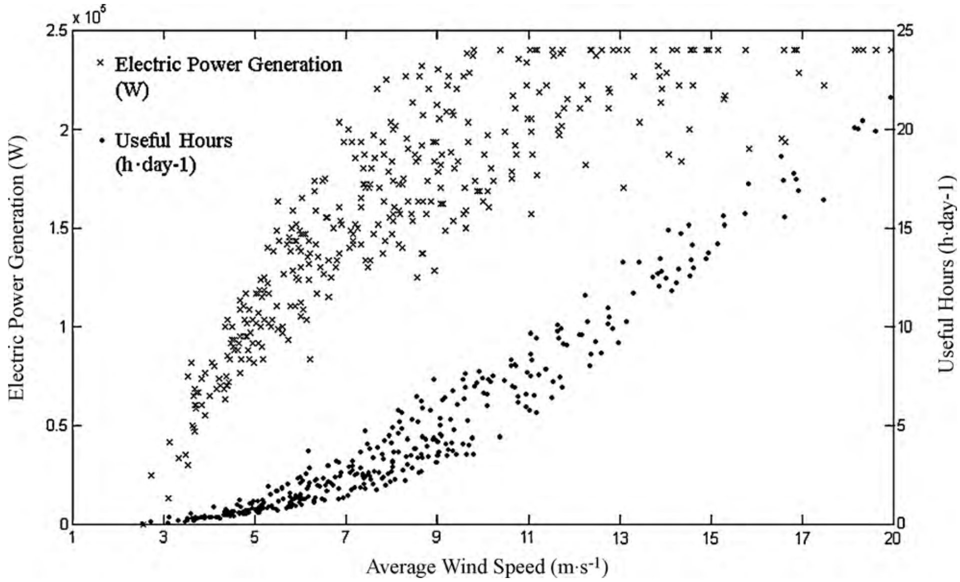

Fig. 2. Electric power generation and useful hours between 3 and 21 m s^{-1} of Cabo San Lucas, Baja California Sur meteorological station 2008.

Table 1
Average wind speed (m s^{-1}) from 2000 to 2008 per EMA.

ID	2000 (m s^{-1})	2001 (m s^{-1})	2002 (m s^{-1})	2003 (m s^{-1})	2004 (m s^{-1})	2005 (m s^{-1})	2006 (m s^{-1})	2007 (m s^{-1})	2008 (m s^{-1})
Ata	–	–	–	–	–	–	–	2.21	2.19
Aca	2.48	1.53	1.01	0.64	1.54	2.05	–	2.12	–
Ayu	–	–	–	–	–	–	–	–	1.50
AMe	–	–	–	1.76	1.83	1.76	1.64	1.77	1.38
Ala	–	–	–	–	–	–	3.31	2.72	2.72
Alt	–	–	–	–	2.84	2.62	2.82	3.47	3.56
Alv	3.79	5.62	3.96	3.85	4.16	4.72	5.26	4.28	4.61
Ang	1.66	2.58	2.42	2.37	2.36	2.41	2.30	1.52	0.79
Apa	–	–	–	1.67	1.57	1.27	–	1.92	1.86
Aco	2.05	2.58	2.55	2.59	2.63	2.72	2.73	2.60	2.53
Ato	–	–	–	–	–	–	–	–	0.90
BLA	3.23	4.78	4.80	2.86	5.52	4.69	4.81	4.58	4.73
Bas	0.81	1.55	1.88	1.49	1.52	1.35	1.46	1.45	1.48
CSL	3.16	4.52	3.49	2.67	4.63	4.78	–	4.02	4.60
Cab	–	–	–	–	–	–	–	–	2.32
Ckl	–	–	–	1.17	1.80	1.56	1.40	0.68	0.44
Cal	–	–	–	–	–	2.49	2.27	2.42	2.35
Cam	1.60	2.05	1.63	0.13	1.18	2.53	2.30	2.35	2.31
Can	4.43	4.23	8.17	5.18	4.67	4.74	3.96	3.35	3.93
Cta	–	–	–	–	–	2.94	3.05	3.03	3.00
CAl	1.51	1.55	1.56	1.71	1.50	1.95	1.86	1.89	1.79
CAt	–	–	–	1.01	1.14	1.19	1.19	1.19	1.22
CCo	1.69	2.86	2.56	1.38	1.39	2.43	2.53	2.69	2.56
CCu	–	–	–	–	–	–	–	–	1.53
CCa	2.17	3.25	1.99	–	1.44	2.84	3.07	2.99	1.66
CFe	–	–	–	–	–	–	–	–	1.23
Cel	–	–	–	–	3.76	4.20	3.99	4.32	4.36
CEMCAS	–	–	–	–	–	2.89	2.69	2.69	2.68
CPGM	3.93	4.65	5.01	3.25	3.40	4.50	3.66	3.38	3.39
CCt	3.73	2.60	2.46	3.30	2.62	3.28	3.23	2.73	1.95
Cha	2.22	2.14	2.01	1.93	1.49	0.97	2.03	1.90	1.81
Che	4.28	3.76	5.45	4.29	5.37	3.59	–	4.21	3.40
Chi	1.72	1.64	1.65	1.54	1.01	1.34	1.58	1.62	1.43
Chp	1.30	0.94	0.81	0.76	1.08	0.90	1.24	1.28	0.87
Cit	–	–	–	–	–	–	1.69	0.90	0.86
CDe	–	–	–	–	–	–	–	2.04	2.14
CFd	–	–	–	–	–	–	–	–	1.57
CMa	–	–	–	–	–	–	3.08	2.96	3.22
CVa	–	–	–	–	–	–	3.62	2.99	3.10
Cor	–	–	–	–	–	–	–	–	0.88
Coz	–	–	–	–	–	–	3.45	3.14	3.98
CCi	–	–	–	–	–	–	–	–	2.91
Dzi	–	–	–	–	–	–	–	–	3.88
Eco	–	–	–	–	–	–	–	–	1.33
EFu	–	–	–	–	–	–	–	–	1.18

Table 1 (*Continued*)

ID	2000 ($m\,s^{-1}$)	2001 ($m\,s^{-1}$)	2002 ($m\,s^{-1}$)	2003 ($m\,s^{-1}$)	2004 ($m\,s^{-1}$)	2005 ($m\,s^{-1}$)	2006 ($m\,s^{-1}$)	2007 ($m\,s^{-1}$)	2008 ($m\,s^{-1}$)
EVe	–	–	–	–	–	–	–	–	1.48
Esc	–	–	–	–	–	1.57	–	1.76	1.66
ENCBxII	–	–	–	–	–	–	–	–	1.32
ENCB	2.40	2.42	2.41	2.11	2.26	2.48	2.15	2.43	2.23
Est	–	–	–	–	–	–	–	–	0.16
Gua	–	2.82	2.67	2.07	2.49	2.35	0.55	–	–
GDO	1.50	2.03	1.91	1.59	1.04	2.06	0.95	0.67	0.24
HeB	–	–	–	–	–	–	–	2.99	2.86
Hua	2.33	2.49	2.50	2.40	3.21	3.09	2.83	2.87	2.29
Hch	–	–	–	–	–	–	–	–	0.43
Hue	1.35	1.40	1.54	1.19	0.61	0.41	0.52	1.31	1.14
Hui	–	–	–	–	–	–	0.62	1.86	1.98
Hpn	3.11	2.79	2.67	3.11	4.69	3.28	2.27	2.85	3.00
Igu	–	–	–	–	–	1.39	1.24	1.28	1.10
IMTA	1.98	2.00	1.35	1.26	1.35	1.87	1.93	1.99	2.08
Ixt	–	–	–	–	–	–	1.28	3.68	2.62
IzM	2.18	2.81	2.77	2.73	2.67	2.69	2.77	2.08	–
Jal	2.55	2.46	2.58	2.66	2.66	2.32	2.92	2.23	2.87
Jau	–	–	–	–	–	–	–	–	0.42
Jim	–	–	–	–	–	2.75	2.65	2.50	2.58
Joc	2.41	2.22	2.11	2.02	1.57	0.67	0.59	1.07	–
JMM	–	–	–	–	–	–	–	–	2.84
LFl	–	–	–	–	–	–	–	–	2.30
LRu	–	–	–	–	–	3.31	3.71	3.81	3.79
LVe	–	–	–	2.03	2.07	1.98	1.74	1.38	0.98
LCo	–	1.50	1.38	1.62	1.05	0.59	0.79	1.55	0.90
Mag	2.57	2.47	2.61	2.55	2.46	2.37	2.44	2.39	2.42
Mat	1.78	4.72	2.26	3.43	2.13	3.41	2.26	2.79	2.90
Mha	–	–	–	1.93	2.41	2.08	2.35	2.26	1.78
MRo	–	–	–	2.66	2.91	2.34	–	2.82	2.56
Mer	3.59	3.32	–	–	–	–	3.91	3.04	2.84
Mex	2.39	3.01	3.15	2.98	2.99	2.84	2.87	1.00	3.03
Mon	–	–	–	–	–	–	–	–	1.28
MoM	–	–	–	–	–	–	–	–	1.12
Nev	3.73	4.48	4.56	4.57	4.95	4.76	4.13	4.35	2.75
Nic	–	–	–	–	–	–	–	–	1.18
Noch	–	–	–	–	–	2.76	2.75	2.63	2.37
Nog	–	–	–	–	–	–	–	–	1.98
NuR	–	–	–	–	–	–	0.63	2.03	2.04
Obi	–	–	–	–	–	–	0.99	2.18	1.13
Oji	–	–	–	–	–	–	–	–	1.77
Oxk	–	–	–	–	–	–	–	–	1.02
Pach	3.22	3.49	3.62	3.50	3.52	2.62	1.03	3.21	3.21
Pal	–	–	–	1.73	1.55	1.46	1.10	0.59	0.86
Par	–	–	–	–	–	–	2.59	2.70	2.61
PIP	–	–	–	–	–	–	–	–	1.45
Pet	–	–	–	1.78	2.33	2.22	–	2.27	0.84
PiNa	–	–	–	1.89	2.01	1.78	1.20	1.00	1.22
PALR	2.58	2.90	2.26	1.21	1.21	2.26	2.45	2.56	2.45
PAll	1.63	2.26	2.02	1.70	0.78	0.46	0.53	1.85	1.89
PECu	2.99	3.44	3.42	0.71	–	2.32	3.39	3.20	3.39
PELZ	2.82	2.98	3.15	2.84	1.79	1.94	3.04	3.07	2.90
PLCa	–	–	–	–	–	1.83	2.04	1.81	1.97
PMad	1.62	1.90	1.82	1.68	1.35	1.75	1.72	1.70	1.62
PuA	–	3.07	3.36	3.78	3.78	3.61	0.55	3.72	3.08
RLag	4.87	3.70	–	–	–	–	2.74	2.74	3.09
RTom	1.61	2.46	2.46	2.13	1.23	1.04	–	2.34	2.13
SFer	–	–	–	–	–	–	–	–	1.78
SJuan	–	–	–	–	–	–	–	–	1.90
SJDG	–	–	–	–	–	–	–	–	1.08
SNico	–	–	–	–	–	–	–	–	1.65
SLRC	–	–	–	–	–	–	–	–	2.49
SQtin	2.05	2.93	2.79	2.37	2.22	2.73	2.78	2.62	0.58
SCe	–	–	–	–	–	3.08	2.68	1.10	1.20
SRos	2.13	3.23	3.32	3.18	–	3.11	3.25	3.22	2.88
SMN	2.48	2.45	2.45	2.39	2.49	2.44	2.28	2.33	–
Sian	–	–	–	–	3.33	3.44	2.62	3.16	3.50
Son	–	–	–	–	–	–	–	–	1.82
Tan	–	–	–	2.35	2.69	2.20	2.79	3.03	3.71
Tep	–	–	–	–	–	2.14	2.08	2.03	1.24
Tez	2.38	3.05	2.58	2.07	0.85	2.33	2.69	2.45	1.49
Tlan	–	–	–	–	–	–	–	–	0.91
Tiz	3.04	3.22	3.18	3.13	2.77	1.24	1.15	3.06	3.10
TCom	–	–	–	–	–	–	–	–	1.20
Tux	–	–	–	–	–	–	1.19	1.21	1.19
UTT	–	–	–	–	–	–	3.23	3.80	3.13
Uri	2.49	2.22	2.38	–	–	2.04	2.18	2.03	1.77

Table 1 (*Continued*)

ID	2000 (m s^{-1})	2001 (m s^{-1})	2002 (m s^{-1})	2003 (m s^{-1})	2004 (m s^{-1})	2005 (m s^{-1})	2006 (m s^{-1})	2007 (m s^{-1})	2008 (m s^{-1})
Uru	–	–	–	–	–	–	–	1.36	1.11
VCa	–	–	–	–	–	–	–	–	1.74
VAhu	–	–	–	–	–	–	–	–	1.62
VOc	–	–	–	–	–	–	–	–	1.46
Vigran	–	–	–	–	–	–	–	–	1.74
Yec	–	–	–	–	–	–	1.48	1.88	2.82
Yoh	–	–	–	–	–	–	–	–	0.86
Zac	–	3.34	3.70	3.65	3.02	3.32	3.30	3.43	3.44
Zpan	–	–	–	–	–	–	–	–	0.83
Zih	–	–	–	–	–	–	–	–	1.53
Zim	–	–	–	–	–	–	–	–	1.16
μ (m s^{-1})	2.51	2.85	2.76	2.29	2.39	2.43	2.30	2.43	2.06

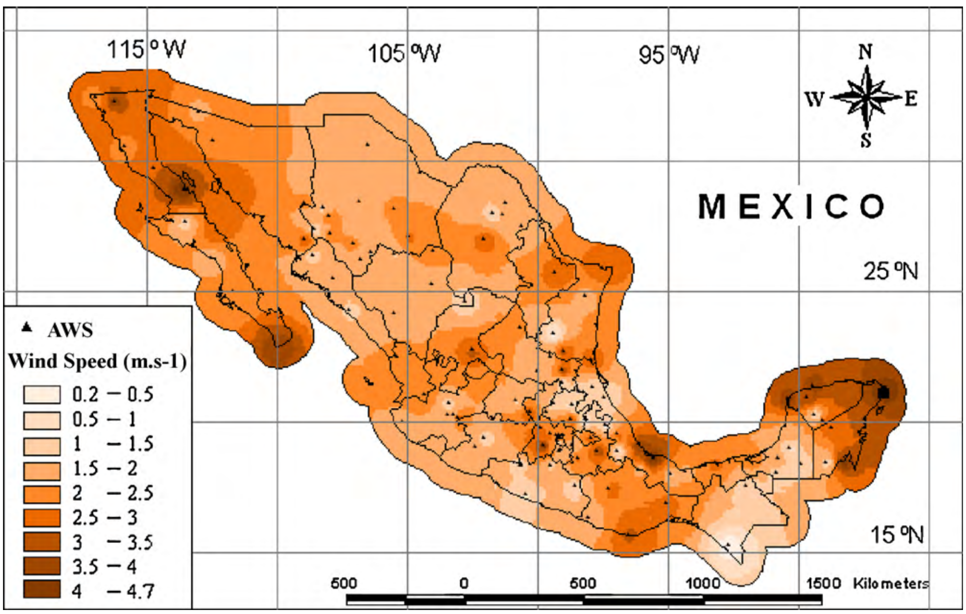

Fig. 3. Wind speed mapping.

Table 2
Working hours (h day^{-1}) between 3 to 21 (m s^{-1}) of wind from 2000 to 2008 per EMA.

ID	2000 (h day^{-1})	2001 (h day^{-1})	2002 (h day^{-1})	2003 (h day^{-1})	2004 (h day^{-1})	2005 (h day^{-1})	2006 (h day^{-1})	2007 (h day^{-1})	2008 (h day^{-1})
Ata	–	–	–	–	–	–	–	1738	1752
Aca	2491	1837	1167	790	1040	1633	–	1935	–
Ayu	–	–	–	–	–	–	–	–	1189
AMe	–	–	–	1411	1438	1501	1282	1559	1129
Ala	–	–	–	–	–	–	4580	4015	4015
Alt	–	–	–	–	3105	2875	3545	4850	4705
Alv	5715	6970	5450	5970	5740	6370	6810	5915	5940
Ang	1737	2784	2453	2445	2260	2405	2200	1530	907
Apa				1399	1257	1327	–	1622	1580
Aco	2173	2943	2862	2883	2907	3208	3042	2900	2788
Ato	–	–	–	–	–	–	–	–	51
BLA	3579	5103	4296	3051	3625	5157	5084	5034	4865
Bas	922	1959	2338	1791	1467	1176	1652	1698	1681
CSL	3727	5267	4194	3272	5483	5610	–	4735	5747
Cab	–	–	–	–	–	–	–	–	2997
Ckl	–	–	–	549	1132	933	1128	320	136
Cal	–	–	–	–	–	2756	2560	2707	2601
Cam	1732	2832	2231	25	1271	3151	2732	2661	2509
Can	4085	4195	4330	4545	4765	5050	4900	4755	4685
Cta	–	–	–	–	–	3764	3733	3851	3945
CAl	240	425	590	725	660	900	985	1045	1005
CAt	–	–	–	168	162	152	155	152	169
CCo	2014	3572	2974	1651	1323	2794	3019	3298	2951
CCu	–	–	–	–	–	–	–	–	1986
CCa	3216	4729	2693	–	1824	3636	4341	4179	2082
CFe	–	–	–	–	–	–	–	–	765
Cel	–	–	–	–	5770	6360	6185	7290	6645
CEMCAS	–	–	–	–	–	3241	2890	2938	2968

Table 2 (*Continued*)

ID	2000 (h day^{-1})	2001 (h day^{-1})	2002 (h day^{-1})	2003 (h day^{-1})	2004 (h day^{-1})	2005 (h day^{-1})	2006 (h day^{-1})	2007 (h day^{-1})	2008 (h day^{-1})
CPGM	4290	5350	5345	4185	4985	5440	4840	4815	4965
CCt	5052	3504	3381	4272	3683	4568	4167	3630	2535
Cha	2097	2302	1642	1504	1559	848	1889	1753	1385
Che	7370	5815	8080	7070	2760	5790	–	6535	4965
Chi	1548	1580	1564	1446	1069	1234	1268	1545	1252
Chp	1139	960	979	698	1033	760	1068	1078	886
Cit	–	–	–	–	–	–	255	925	880
CDe	–	–	–	–	–	–	–	1619	1696
CFd	–	–	–	–	–	–	–	–	1530
CMa	–	–	–	–	–	–	4625	4330	5130
CVa	–	–	–	–	–	–	6285	4200	4260
Cor	–	–	–	–	–	–	–	–	450
Coz	–	–	–	–	–	–	5430	4215	5635
CCi	–	–	–	–	–	–	–	–	3850
Dzi	–	–	–	–	–	–	–	–	4882
Eco	–	–	–	–	–	–	–	–	579
EFu	–	–	–	–	–	–	–	–	805
EVe	–	–	–	–	–	–	–	–	1912
Esc	–	–	–	–	–	1655	–	1752	1863
ENCB II	–	–	–	–	–	–	–	–	822
ENCB	2442	2590	2506	2148	2391	2546	2153	2541	2177
Est	–	–	–	–	–	–	–	–	2
Gua	–	3280	3286	2625	3154	2862	561	–	–
GDO	1381	1549	1067	1600	949	2043	740	526	129
HeB	–	–	–	–	–	–	–	3485	3410
Hua	2415	2720	2655	2490	3960	3600	2970	3100	2095
Hch	–	–	–	–	–	–	–	–	37
Hue	718	903	1129	805	460	293	180	774	700
Hui	–	–	–	–	–	–	389	1372	1565
Hpn	4285	3530	3570	4600	6110	4965	2030	4220	8002
Igu	–	–	–	–	–	335	277	320	314
IMTA	748	1016	686	552	2685	873	1038	1141	1202
Ixt	–	–	–	–	–	–	1304	4392	3924
IzM	2527	3137	3064	3016	2906	3040	3017	2109	–
Jal	2965	2725	2675	3415	3430	2710	3470	2130	3390
Jau	–	–	–	–	–	–	–	–	233
Jim	–	–	–	–	–	3079	2681	2685	2821
Joc	2655	2492	2164	1929	1149	623	348	561	–
JMM	–	–	–	–	–	–	–	–	3155
LFl	–	–	–	–	–	–	–	–	2932
LRu	–	–	–	–	–	4477	4873	5184	5196
LVe	–	–	–	1919	2191	2188	1975	1758	1324
LCo	–	990	906	1025	680	462	421	882	649
Mag	2588	2587	2679	2664	2578	2456	2531	2554	2502
Mat	2530	7055	3270	4700	3055	5840	3090	3995	4840
Mha	–	–	–	960	2890	1425	2395	2045	825
MRo	–	–	–	3583	3967	3040	–	3812	3558
Mer	6030	5920	–	–	–	–	7225	4265	3580
Mex	2752	3342	3490	3331	4334	3987	4039	1167	3418
Mon	–	–	–	–	–	–	–	–	551
MoM	–	–	–	–	–	–	–	–	801
Nev	4915	6180	6144	5959	6438	6267	5621	6037	3780
Nic	–	–	–	–	–	–	–	–	850
Noch	–	–	–	–	–	3137	3022	2929	2715
Nog	–	–	–	–	–	–	–	–	1943
NuR	–	–	–	–	–	–	385	1689	1835
Obi	–	–	–	–	–	–	1265	3280	1445
Oji	–	–	–	–	–	–	–	–	1635
Oxk	–	–	–	–	–	–	–	–	777
Pach	3404	3903	3983	3915	4031	3177	1201	3719	3793
Pal	–	–	–	899	1069	751	645	333	412
Par	–	–	–	–	–	–	1975	2160	1867
PIP	–	–	–	–	–	–	–	–	1774
Pet	–	–	–	1659	2283	2413	–	2106	937
PiNa	–	–	–	1583	1726	1585	1408	1318	1221
PALR	2895	3623	2482	1271	1012	2349	2351	2657	2326
PAll	1233	1943	1629	1260	650	346	306	1288	1384
PECu	3699	4263	4423	901	–	2988	4208	4234	4301
PELZ	2796	3571	3749	3404	3052	2415	3433	3574	3408
PLCa	–	–	–	–	–	1370	2315	1380	1709
PMad	1226	1459	1391	1171	1027	1140	974	1000	874
PuA	–	4412	5175	5270	4705	5588	424	5638	4301
RLag	6930	5235	–	–	–	–	3655	3530	4005
RTom	1601	2443	2502	2342	1611	1329	–	2378	142
SFer	–	–	–	–	–	–	–	–	205
SJuan	–	–	–	–	–	–	–	–	2400
SJDG	–	–	–	–	–	–	–	–	715

Table 2 (*Continued*)

ID	2000 ($h\,day^{-1}$)	2001 ($h\,day^{-1}$)	2002 ($h\,day^{-1}$)	2003 ($h\,day^{-1}$)	2004 ($h\,day^{-1}$)	2005 ($h\,day^{-1}$)	2006 ($h\,day^{-1}$)	2007 ($h\,day^{-1}$)	2008 ($h\,day^{-1}$)
SNico	–	–	–	–	–	–	–	–	2190
SLRC	–	–	–	–	–	–	–	–	3271
SQtin	2668	3542	3528	3037	2671	3219	3222	3373	613
SCe	–	–	–	–	–	4035	3624	1484	1439
SRos	3077	4502	4550	4142	–	4217	4273	4380	3746
SMN	2663	2681	2662	2595	2564	2659	2503	2253	–
Sian	–	–	–	–	4975	5350	2415	4520	5260
Son	–	–	–	–	–	–	–	–	1982
Tan	–	–	–	3120	3175	2665	4195	4350	5345
Tep	–	–	–	–	–	1495	1391	1510	963
Tez	2688	3839	2966	2295	1046	2776	3052	2870	1791
Tlan	–	–	–	–	–	–	–	–	273
Tiz	4257	4348	4439	4273	3811	1628	1137	4366	4353
TCom	–	–	–	–	–	–	–	–	688
Tux	–	–	–	–	–	–	65	140	400
UTT	–	–	–	–	–	–	4340	5290	3837
Uri	2007	1569	1376	–	–	1420	1643	1482	1513
Uru	–	–	–	–	–	–	–	1138	1072
VCa	–	–	–	–	–	–	–	–	2444
VAhu	–	–	–	–	–	–	–	–	1373
VOc	–	–	–	–	–	–	–	–	1190
Vigran	–	–	–	–	–	–	–	–	1932
Yec	–	–	–	–	–	–	1765	2185	3660
Yoh	–	–	–	–	–	–	–	–	820
Zac	–	4335	4420	4785	2920	4260	4110	4960	4935
Zpan	–	–	–	–	–	–	–	–	58
Zih	–	–	–	–	–	–	–	–	1201
Zim	–	–	–	–	–	–	–	–	856
μ ($h\,day^{-1}$)	2896	3356	3024	2545	2643	2791	2616	2810	2292

Table 3
Electric power generation (KW) for each EMA and per wind generator installed.

ID	2000 (KW)	2001 (KW)	2002 (KW)	2003 (KW)	2004 (KW)	2005 (KW)	2006 (KW)	2007 (KW)	2008 (KW)
Ata	–	–	–	–	–	–	–	1832	1860
Aca	4119	2755	1864	1253	1606	3022	–	12,048	–
Ayu	–	–	–	–	–	–	–	–	2466
AMe	–	–	–	3079	3295	2672	2311	2887	2558
Ala	–	–	–	–	–	–	12,654	11,568	11,568
Alt	–	–	–	–	11,644	5074	10,069	20,176	24,344
Alv	17,168	69,875	34,497	16,778	27,673	49,779	57,539	34,086	51,755
Ang	3153	5700	4499	4584	4370	4524	3971	2615	2054
Apa	–	–	–	2862	2101	2642	–	3185	2880
Aco	6868	8791	6909	8051	8788	8994	9668	7292	8094
Ato	–	–	–	–	–	–	–	–	55
BLA	38,974	59,504	60,662	38,209	46,989	56,189	58,001	54,586	54,960
Bas	1292	3464	4716	2594	2249	1900	2320	2412	2551
CSL	32,303	44,129	42,484	25,175	43,551	52,713	–	37,422	44,682
Cab	–	–	–	–	–	–	–	–	8917
Ckl	–	–	–	549	1439	884	1140	315	136
Cal	–	–	–	–	–	6739	5825	6462	6202
Cam	2321	5381	4845	33	1595	5269	4393	4092	3378
Can	26,451	20,780	143,388	32,592	24,107	27,128	14,651	9088	16,587
Cta	–	–	–	–	–	11,087	12,599	13,952	14,186
CAl	264	600	569	1005	823	914	1042	2531	1097
CAt	–	–	–	222	190	156	175	185	183
CCo	3739	10,099	7034	4087	2680	5488	6811	7823	7118
CCu	–	–	–	–	–	–	–	–	7369
CCa	5968	11,001	7731	–	2691	6228	7637	7310	3182
CFe	–	–	–	–	–	–	–	–	1416
Cel	–	–	–	–	15,275	28,003	17,842	24,124	28,506
CEMCAS	–	–	–	–	–	9344	8272	7108	7265
CPGM	33,680	47,171	62,558	10,163	11,830	42,942	19,797	11,250	13,118
CCt	19,989	14,959	12,486	15,419	13,443	18,870	15,293	15,526	13,055
Cha	4204	4760	2924	2315	3410	2952	4541	3551	1730
Che	19,899	14,635	47,300	18,912	36,089	14,124	–	22,563	9133
Chi	3384	3432	3127	2656	2478	2140	2159	3291	2237
Chp	3086	2513	2496	2006	2267	1926	2710	2748	2242
Cit	–	–	–	–	–	–	194	1012	996
CDe	–	–	–	–	–	–	–	4404	4950
CFd	–	–	–	–	–	–	–	–	3506
CMa	–	–	–	–	–	–	7478	7035	9038
CVa	–	–	–	–	–	–	10,108	4781	5917
Cor	–	–	–	–	–	–	–	–	733
Coz	–	–	–	–	–	–	10,410	9528	24,130
CCi	–	–	–	–	–	–	–	–	32,990

Table 3 (*Continued*)

ID	2000 (KW)	2001 (KW)	2002 (KW)	2003 (KW)	2004 (KW)	2005 (KW)	2006 (KW)	2007 (KW)	2008 (KW)
Dzi	–	–	–	–	–	–	–	–	47,122
Eco	–	–	–	–	–	–	–	–	895
EFu	–	–	–	–	–	–	–	–	1734
EVe	–	–	–	–	–	–	–	–	3173
Esc	–	–	–	–	–	2569	–	2932	2957
ENCB II	–	–	–	–	–	–	–	–	1027
ENCB	4619	5000	4921	4241	4522	4633	4192	4529	3796
Est	–	–	–	–	–	–	–	–	14
Gua	–	16,459	14,512	11,087	11,627	10,093	1578	–	–
GDO	1908	1993	2009	3219	1684	3600	1783	1329	336
HeB	–	–	–	–	–	–	–	14,353	10,325
Hua	4144	6928	7877	5981	14,683	13,171	10,805	11,115	4989
Hch	–	–	–	–	–	–	–	–	32
Hue	1077	1106	1497	1048	563	472	260	954	812
Hui	–	–	–	–	–	–	512	1783	2001
Hpn	9848	5442	5287	8803	45,121	8921	2992	5837	11,066
Igu	–	–	–	–	–	491	416	519	838
IMTA	930	1169	832	721	1673	1098	1169	1230	1324
Ixt	–	–	–	–	–	–	6421	20,897	17,060
IzM	8170	9706	9349	8378	8110	8196	8955	6592	–
Jal	3875	3263	8677	4002	5293	3906	12,746	2547	9010
Jau	–	–	–	–	–	–	–	–	244
Jim	–	–	–	–	–	9251	8491	8297	8447
Joc	5268	4392	3116	2712	1665	903	592	848	–
JMM	–	–	–	–	–	–	–	–	4886
LFl	–	–	–	–	–	–	–	–	8693
LRu	–	–	–	–	–	17,432	19,819	23,075	23,044
LVe	–	–	–	4356	5124	4773	4752	4541	3067
LCo	–	1277	1117	1343	887	563	507	956	755
Mag	10,738	10,404	10,766	9981	8369	7770	8748	9038	9965
Mat	6509	36,922	7066	25,376	9183	10,942	11,273	18,970	10,329
Mha	–	–	–	900	3610	1545	2915	2506	1183
MRo	–	–	–	8183	7794	5933	–	7359	7171
Mer	10,576	9385	–	–	–	–	12,694	6264	5204
Mex	11,326	12,195	15,545	13,068	6649	6007	5774	1639	13,688
Mon	–	–	–	–	–	–	–	–	1078
MoM	–	–	–	–	–	–	–	–	1692
Nev	30,512	37,449	39,646	38,879	49,985	45,953	30,392	35,965	22,443
Nic	–	–	–	–	–	–	–	–	945
Noch	–	–	–	–	–	10,029	9575	9515	8047
Nog	–	–	–	–	–	–	–	–	9115
NuR	–	–	–	–	–	–	908	3899	4056
Obi	–	–	–	–	–	–	2202	15,436	2359
Oji	–	–	–	–	–	–	–	–	6537
Oxk	–	–	–	–	–	–	–	–	984
Pach	33,524	34,041	34,835	32,352	32,946	27,560	7865	24,483	25,548
Pal	–	–	–	1209	1310	851	698	419	442
Par	–	–	–	–	–	–	4424	5245	4822
PIP	–	–	–	–	–	–	–	–	8590
Pet	–	–	–	3569	4385	4754	–	4178	1806
PiNa	–	–	–	2260	2410	2273	1952	1946	1765
PALR	6509	12,985	7844	6720	3491	4956	6914	7792	7264
PAll	2749	4572	3605	2385	1762	902	918	2356	2601
PECu	20,995	19,197	20,718	4453	–	12,965	18,716	17,546	19,388
PELZ	9180	9587	12,336	11,343	9527	8905	11,247	12,336	10,397
PLCa	–	–	–	–	–	1477	2403	1221	1434
PMad	2256	2346	2308	1843	1696	1554	1296	1229	1148
PuA	–	16,169	13,773	19,798	16,453	18,536	679	17,259	9660
RLag	37,928	22,984	–	–	–	–	11,127	9828	13,946
RTom	2928	4773	4381	4369	3165	2935	–	4218	1721
SFer	–	–	–	–	–	–	–	–	7690
SJuan	–	–	–	–	–	–	–	–	2961
SJDG	–	–	–	–	–	–	–	–	1505
SNico	–	–	–	–	–	–	–	–	7024
SLRC	–	–	–	–	–	–	–	–	12,070
SQtin	8402	9910	11,235	10,541	7509	9834	9545	10,533	2524
SCe	–	–	–	–	–	11,108	12,103	5543	4580
SRos	8294	13,699	15,794	12,862	–	12,765	14,331	17,214	14,446
SMN	4710	5059	5093	4665	4810	4883	4529	4461	–
Sian	–	–	–	–	9088	10,329	4430	5744	11,135
Son	–	–	–	–	–	–	–	–	3663
Tan	–	–	–	7281	7177	3591	10,669	10,733	19,889
Tep	–	–	–	–	–	1727	1809	1915	1381
Tez	7997	14,220	8961	6775	4473	8118	8680	8075	5705
Tlan	–	–	–	–	–	–	–	–	239
Tiz	10,427	15,069	10,504	9609	8686	4874	2999	8838	8987
TCom	–	–	–	–	–	–	–	–	1385

Table 3 (*Continued*)

ID	2000 (KW)	2001 (KW)	2002 (KW)	2003 (KW)	2004 (KW)	2005 (KW)	2006 (KW)	2007 (KW)	2008 (KW)
Tux	–	–	–	–	–	–	52	116	387
UTT	–	–	–	–	–	–	14,305	26,967	16,696
Uri	6173	3560	4982	–	–	3585	4114	3409	3820
Uru	–	–	–	–	–	–	–	1534	2008
VCa	–	–	–	–	–	–	–	–	7343
VAhu	–	–	–	–	–	–	–	–	22,449
VOc	–	–	–	–	–	–	–	–	2656
Vigran	–	–	–	–	–	–	–	–	3636
Yec	–	–	–	–	–	–	2916	4950	16,469
Yoh	–	–	–	–	–	–	–	–	1607
Zac	–	20,670	34,913	22,697	18,342	16,781	19,101	16,713	13,357
Zpan	–	–	–	–	–	–	–	–	52
Zih	–	–	–	–	–	–	–	–	1557
Zim	–	–	–	–	–	–	–	–	1199
μ (kW)	10,836	14,030	16,116	8940	10,074	9935	8224	8995	7973

recorded at the Cabo San Lucas AWS in 2008, the annual number of useful hours of wind, and the electrical energy that could be generated.

Fig. 4 shows a map of Mexico on which are represented the mean multiannual hours of useful wind (i.e., $>3\ \mathrm{m\ s^{-1}}$). Nearly the entire country has over 1700 useful hours of wind per year showing Mexico to be a country of great wind power potential – wind farms that enjoy a minimum of 1700 useful hours of wind per year are viable [16]. The States of Chihuahua, Durango, Zacatecas, Sinaloa, San Luís Potosí, Jalisco, Colima and Michoacán have over 2350 useful hours of wind per year. Northeastern Mexico, the States of Tamaulipas, Hidalgo, Puebla and the central region of Veracruz all have 2350–3200 useful hours of wind per year. The north of Baja California Sur, Coahuila and the south of the Yucatán Peninsula have an even greater potential with 3200–4050 useful hours of wind per year. Finally, the south of the States of Baja California Norte and Baja California Sur, the central region of Coahuila, the north of Nuevo León, the centre of Jalisco, Estado de México, the region of the Isthmus of Tehuantepec and the north of the Yucatán Peninsula have an excellent wind power generating potential with 4050–6500 useful hours of wind per year.

Regression analysis showed the relationship between mean annual wind speed and the mean annual number of useful hours of wind to be strongly correlated (90.3% in regression analysis, 90.4% in quadratic regression) (Fig. 5).

Fig. 6 shows a map revealing the potential electrical power that could be generated per year from the wind in different parts of Mexico. The entire country could generate 2000 kW per wind turbine per year (except for the State of Chiapas); indeed, all but six states could develop 5000 kW per turbine per year, with the States of Baja California Norte, Baja California Sur, Sonora, Chihuahua, Coahuila, Nuevo León, Tamaulipas, Vera Cruz and Oaxaca being home to areas where this figure could even reach 10,000 kW. These results coincide with those reported by other authors [20]; indeed, a wind farm already exists in the area of greatest potential (La Ventosa) in the State of Oaxaca [19]. Central Mexico (including the States of Puebla, Hidalgo, Zacatecas, Tlaxcala and Estado de México) is also home to areas that could generate over 10,000 kW

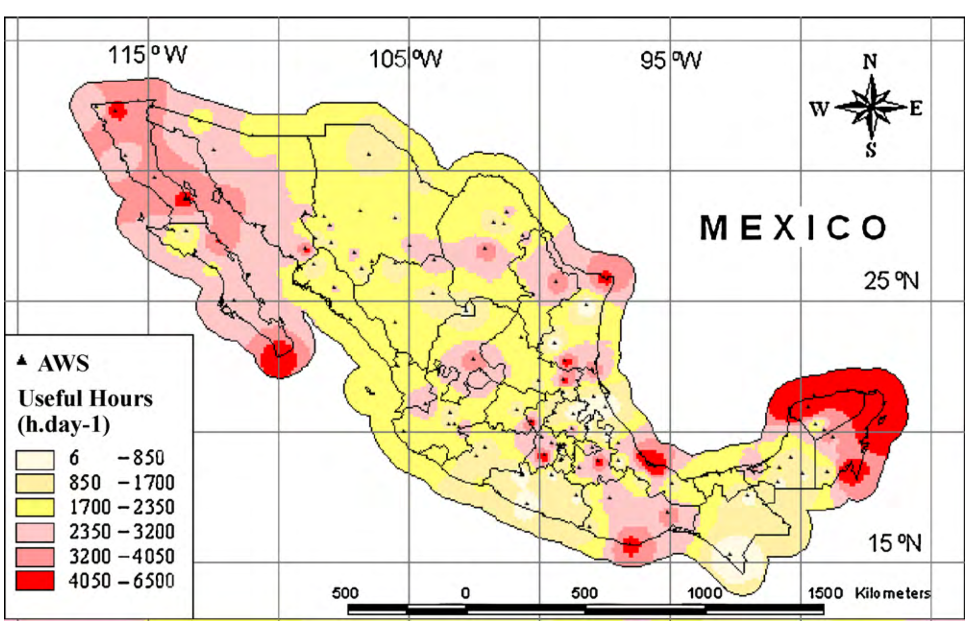

Fig. 4. Useful hours mapping.

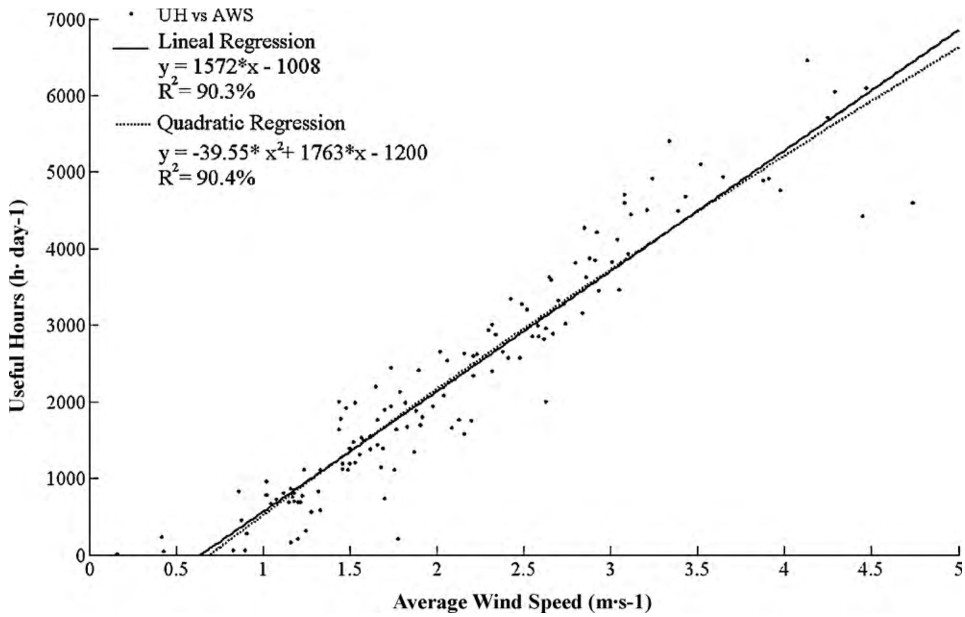

Fig. 5. Statistical analysis between the average wind speed (m s^{-1}) and the useful hours (h day^{-1}) of wind in the country of Mexico.

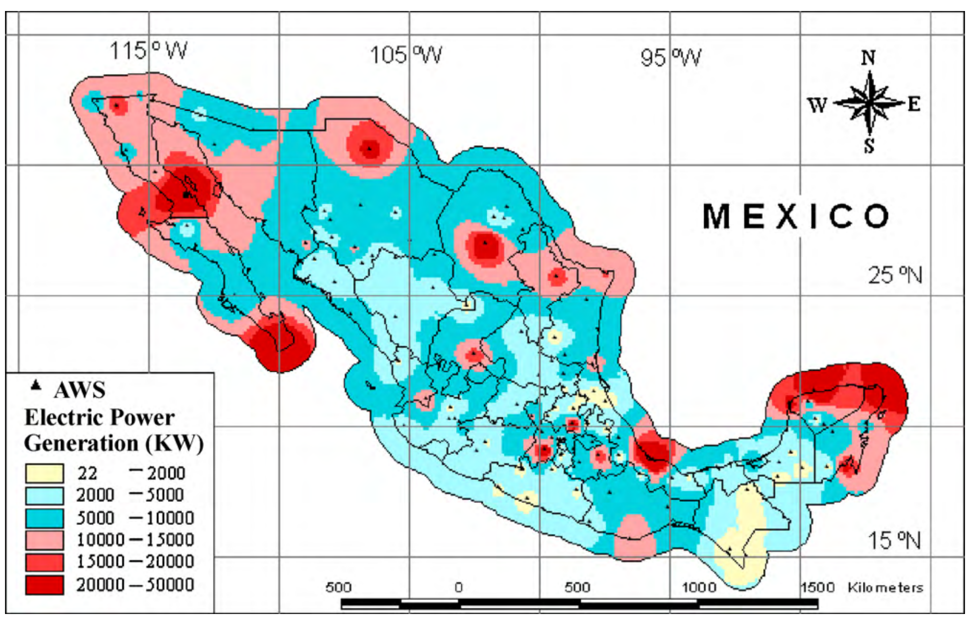

Fig. 6. Wind power generation mapping.

per wind turbine per year. Finally, the Yucatán Peninsula could generate up to 15,000 kW per year per wind turbine installed.

4. Conclusions

Mexico would appear to have great wind power potential since nearly the whole country has more than 1700 h of useful wind (>3 m s^{-1}) per year. The mean annual wind speed and the mean annual number of useful hours of wind (>3 m s^{-1}) are linearly correlated (90.3%). The entire country has the capacity to produce over 2000 kW per year of electrical power per wind turbine installed (except for the State of Chiapas); indeed, this figure is over 5000 kW per year in all but six of Mexico's 31 states.

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References

[1] Denny E. The economics of tidal energy. Energy Policy 2009;37(5):1914–24.
[2] Akdag SA, Dinler A. A new method to estimate Weibull parameters for wind energy applications. Energy Conversion and Management 2009;50(7):1761–6.
[3] Sebitosi AB, y Pillay P. Renewable energy and the environment in South Africa: a way forward. Energy Policy 2008;36(9):3312–6.

[4] Cárdenas R, Pena R, Tobar G, Clare J, Wheeler P, Asher G. Stability analysis of a wind energy conversion system based on a doubly fed induction generator fed by a matrix converter. IEEE Transactions on Industrial Electronics 2009;56 (10):4194–206.
[5] Cook NJ. Towards better estimation of extreme winds. Journal of Wind Engineering and Industrial Aerodynamics 1982;9:295–323.
[6] Wang G, Gavala HN, Skiadas IV, Ahring BK. Wet explosion of wheat straw and codigestion with swine manure: effect on the methane productivity. Waste Management 2009;29(11):2830–5.
[7] Sallem S, Chaabene M, Kamoun MBA. Optimum energy management of a photovoltaic water pumping system. Energy Conversion and Management 2009;50(11):2728–31.
[8] Denny E, O'Malley M. Wind generation, power system operation, and emissions reduction. IEEE Transactions on Power Systems 2006;21(1):341–7.
[9] Nielsen HA, Nielsen TS, Madsen H, Pindado MJSI. Optimal combination of wind power forecasts. Wind Energy 2007;10(5):471–82.
[10] Ma L, Luan SY, Jiang CW, Liu H, Zhang Y. A review on the forecasting of wind speed and generated power. Renewable & Sustainable Energy Reviews 2009;13(4):915–20.
[11] Ammari HD, Al-Maaitah A. Assessment of wind-generation potentiality in Jordan using the site effectiveness approach. Energy 2003;28(15):1579–92.
[12] Gibescu M, Brand AJ, Kling WL. Estimation of variability and predictability of large-scale wind energy in the Netherlands. Wind Energy 2009;12(3):241–60.
[13] Kareem A. Numerical simulation of wind effects: a probabilistic perspective.In: Conference information: 4th international symposium on computational wind engineering (CWE 2006) Japan. Journal of Wind Engineering and Industrial Aerodynamics 2008;96(10–11):1472–97.
[14] Madrid, Spain: Gamesa; 2009. See also http://www.gamesacorp.com/es/productos/aerogeneradores/catalogo-de-aerogeneradores/gamesa-g90-20-mw/gamesa-g90-20-kw
[15] Keyhani A, Ghasemi-Varnamkhasti M, Khanali M, Abbaszadeh R. An assessment of wind energy potential as a power generation source in the capital of Iran, Tehran. Energy 2010;35(1):188–201.
[16] Albadi MH, El-Saadany EF, Albadi HA. Wind to power a new city in Oman. Energy 2009;34(10):1579–86.
[17] Blanco MI. The economics of wind energy. Renewable and Sustainable Energy Reviews 2009;13(6–7):1372–82.
[18] Cancino-Solórzano Y, Xiberta-Bernat J. Statistical analysis of wind power in the region of Veracruz (Mexico). Renewable Energy 2009;34(6):1628–34.
[19] Cadenas E, Rivera W. Short term wind speed forecasting in La Venta, Oaxaca, México, using artificial neural networks. Renewable Energy 2009;34 (1):274–8.
[20] Denver Colorado, USA: NREL, National Renewable Energy Laboratory; 2009. See also http://www.nrel.gov/
[21] Mexico, DF: SMN, Servicio Meteorológico Nacional; 2009. See also http://smn.cna.gob.mx/productos/emas/